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Narrative Review

The Application of Neuromuscular Electrical Stimulation Training in Various Non-neurologic Patient Populations: A Narrative Review

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Abstract

In the last 2 decades, neuromuscular electrical stimulation has been used increasingly in deconditioned patients with the aim of increasing muscle force. Much basic research has been conducted in the area of increasing a muscle's fatigue resistance by neuromuscular electrical stimulation but similarly thorough research with regard to increasing maximal force is missing. Insufficient clinical and basic knowledge exists on the selection of stimulation parameters that will optimize muscle hypertrophy and gains in muscle force. For volitional training, established stimuli for muscle hypertrophy (which more or less parallels maximal muscle force) are muscle tension, metabolic stress, and muscle damage. The present review summarizes findings from clinical and basic research in terms of muscle mechanical as well as acute and chronic physiologic effects of different stimulation protocols, explains the role of the various stimulation parameters in determining the effect of NMES training protocols, and gives clinical recommendations for the choice of stimulation parameters for different patient populations with different training goals, such as increasing muscle force, mass, endurance, or energy consumption. We limit this review to non-neurologic patients, because training goals of neurologic patients are specific to their functional deficits.

Introduction

Since approximately the 1990s, neuromuscular electrical stimulation (NMES) has been used increasingly for the purpose of muscle strengthening in deconditioned patients, for example, in patients before and/or after orthopedic surgery [1-3]. More recently, NMES has been implemented successfully in patients in the intensive care unit to curb the extensive muscle wasting [4]. Few studies have followed a similar aim and have assessed the efficacy of NMES in attenuating muscle wasting in the population of frail, elderly people [5]. Although much basic research has been carried out on how to achieve a more fatigue-resistant muscle by NMES comparing different stimulation protocols in carefully controlled animal experiments [6,7], similar studies following the aim of muscle hypertrophy and muscle strengthening are very rare [8,9]. In fact, a rational for why a chosen stimulation protocol should favor muscle hypertrophy is absent in most studies. There is clearly insufficient clinical and basic knowledge on the selection of stimulation parameters that will optimize muscle hypertrophy and gains in muscle force. In the absence of knowledge on hypertrophic stimuli from NMES, we consider it appropriate to assume that stimuli may be congruent to those from volitional training, notwithstanding that because of a mostly small stimulated muscle mass the effects of NMES generally are smaller compared with volitional training. For volitional training, the current consensus is that the main stimuli for muscle hypertrophy are muscle tension, muscle damage, and metabolic stress [10-13].

The aim of the present review is to explain the specific characteristics of NMES training protocols, to summarize findings from clinical and basic research in terms of muscle mechanical as well as acute and chronic physiologic effects of different stimulation protocols, explain the role of the various stimulation parameters in determining the effect of NMES training protocols, and to give clinical recommendations for the choice of stimulation parameters for different patient populations with different training goals, such as increasing muscle force, mass, endurance, or energy consumption. We limit this review to non-neurologic patients, because the training goals of neurologic patients are specific to their functional deficits.

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Literature Search Strategy

Literature research was performed, including all relevant studies up to October 2014 by searching the Medline/PubMed database and Web of Science using the following search terms: electrical stimulation, electrostimulation, electromyostimulation, muscle stimulation, neuromuscular stimulation, muscle hypertrophy, muscle fiber type, muscle fatigue, muscle force, muscle torque, muscle damage, stimulation frequency, pulse duration, electrical current, and electrode.

Acute Effects of NMES

This section summarizes evidence indicating that the stimuli for muscle hypertrophy with volitional training may also be achieved with NMES.

Force Production

There is much evidence for volitional muscle training that high-force contractions are needed to maximize gains in maximal muscle force [14,15]. Muscle force achieved by NMES usually is measured for the knee extensors by force transducer and reported as a percentage of the maximal voluntary contraction (MVC) force. Evoked torque achieved with NMES has been reported between 20% and 90% and 5% and 112% MVC in 2 reviews on healthy subjects and athletes, respectively [16,17], and is highly dependent on motivation of the subjects [17]. In patient populations, % MVC generally are around or below 30% MVC [18-20]. The force achieved by NMES increases in a sigmoidal manner with increasing stimulation frequency up to approximately 70-80 Hz [21,22], depending on the fiber type composition of the stimulated muscle [23]. With NMES, to achieve optimal force development greater stimulation frequencies are needed than the physiological firing frequency of the nerves because of the synchronous motor unit firing pattern [24]. In contrast to volitional contractions, motor unit recruitment pattern by NMES is nonselective, spatially fixed and temporally synchronous [25].

In summary, extrinsically measured muscle forces achieved with NMES generally are rather low, however, because often only a small portion of the muscle fiber pool is activated, intrinsic forces generated by these fibers may be substantial.

Metabolic Stress

In healthy subjects, oxygen consumption elicited by NMES, measured by spirometric methods, ranged between 7.3 and 14.9 mL*min^{-1}*kg^{-1}, corresponding to a 2- to 4-fold increase from rest [26,27].

On the level of the contracting muscle, NMES-induced contractions may, however, lead to an exaggerated oxygen consumption (VO_2) even at a relatively low mechanical load [28,29]. When VO_2 consumption during contractions of the knee extensors either by volitional or force-matched NMES-induced contractions was compared, VO_2 consumption was greater with NMES (11 versus 8 mL*min^{-1}*kg^{-1} at 46% MVC) [30]. Similarly, in a study using positron emission tomography, Vanderthommen et al measured a greater local oxygen consumption in NMES compared with volitional contractions (3.0 ± 2.3 versus 0.7 ± 0.3 mL O_2*min^{-1}*100 g^{-1}) [29]. The reason for a greater VO_2 demand may be a reduced mechanical efficiency because of the synchronous motor unit activation imposed by NMES, which requires greater frequencies to reach comparable forces [31]. However, compared with volitional whole-body exercise, metabolic demand is relatively low [26], because of the fact that usually only a small muscle mass is stimulated. Therefore, despite the rather low systemic VO_2 demand, some large acute local changes in metabolic parameters are seen during NMES. For example, serum lactate concentrations were higher with NMES of the knee extensors than with volitional cycling at VO_2-matched intensity [27] or compared with force-matched volitional knee extensions [32].

These results suggest that muscle contractions elicited by NMES are characterized by an increased contribution of the anaerobic metabolism. A review by Gregory and Bickel [33] highlights different possible reasons for the increased metabolic demand, which are mainly based on the unique motor unit recruitment pattern associated with NMES: continuous, synchronous, and exhausting contractile activity in a spatially fixed pool of motor units. We summarize that, despite an only moderate increase in systemic oxygen consumption during NMES, large local metabolic demands can be achieved.

Muscle Damage

Muscle damage may be experienced after NMES exercise sessions, particularly at the beginning of the training program. The extent of muscle damage was greater with NMES compared with force-matched volitional concentric and isometric muscle contractions [32,34] and can be similar to damage resulting from eccentric exercise. A potential reason for this may be the synchronous, spatially fixed, and therefore highly fatiguing recruitment pattern of NMES. Increased creatine kinase levels and delayed-onset muscle soreness (DOMS) were experienced even at very low contraction levels, such as 5.4% MVC [35]. NMES has been found to induce muscle damage that is characterized by histologic alteration of muscle fibers and connective tissue [36]. Indeed, Z-line disruption showed a positive correlation with the electrically induced force [35].

As a repair mechanism, NMES can result in remodeling of the skeletal muscle extracellular matrix [37]. Repeated bout effect also is observed with NMES. In